Advances in Planetary Seismology Using Infrasound Signatures on Venus

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Outline

- Prospects for Venus seismic studies
- Earth as Venus analog
- Earth test campaign(s)
- Conclusion and future work

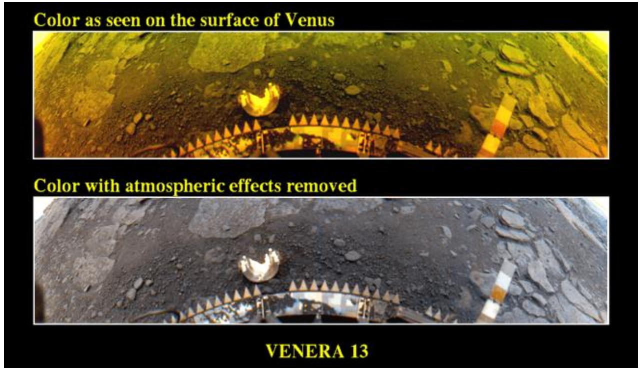
Introduction – Prospects for Venus seismic studies

- Venus is very similar to Earth, but very different

- Very little is known about the internal structure of the planet – there is no evidence of tectonic activity, but the surface is geologically young and shows signs of recent seismic activity

- To understand how Venus evolved, it is necessary to <u>detect the signs of seismic activity</u>.

NASA



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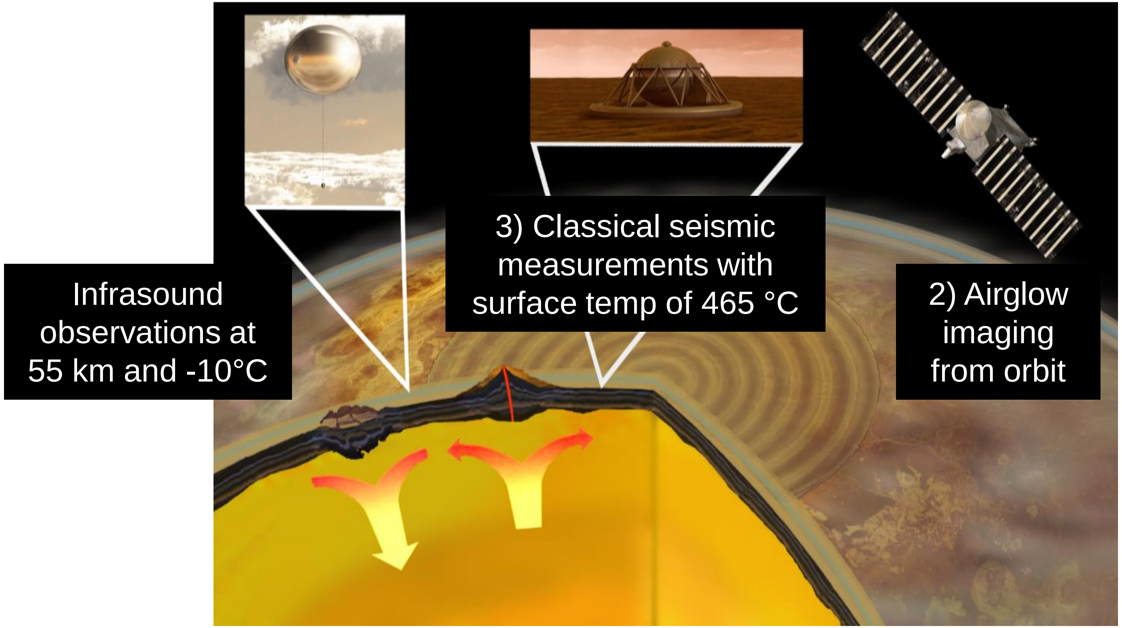
Introduction – Options for seismology on Venus

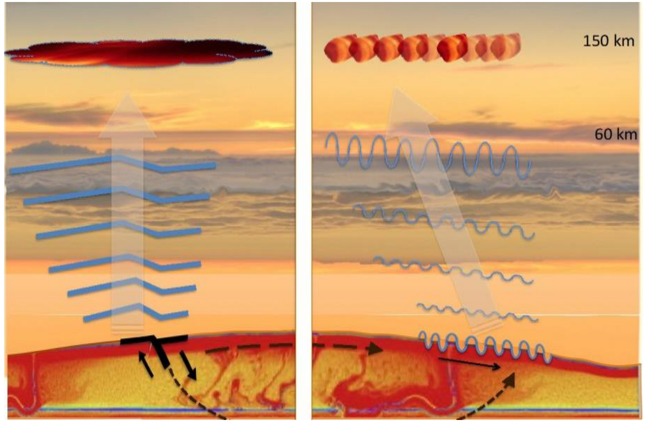


Cutts et al. (2015)

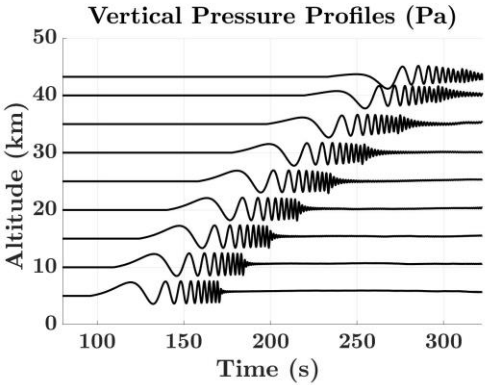
- Surface conditions are harsh – 460 degree C, 90 atmosphere, sulfuric acid-rich environment
- Survival of landers for >1-2 hours is decades away (at best)
- Remote seismology may provide the answer

Introduction – Remote seismology on Venus

- Involves inferring properties of ground motion (location, magnitude, depth etc.) from an aerial or satellite platform
- Energy from ground motion couples to the atmosphere-thermosphere-ionosphere system
- The atmosphere on Venus is much denser – 60x greater coupling than earth
- Infrasonic (<<20 Hz) perturbations travel upward with practically no attenuation till ~80 km



Cutts et al. (2015)

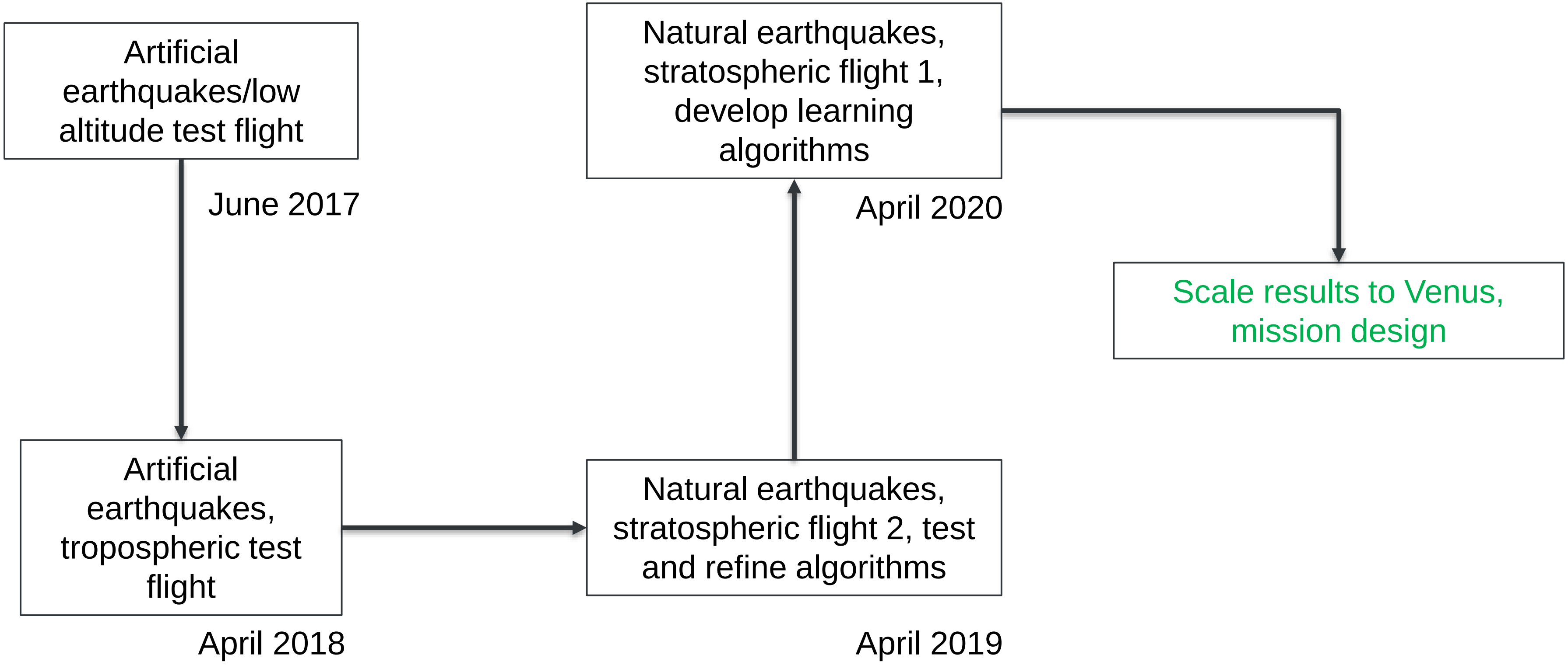


Garcia et al. (2005)

Earth as a Venus analog

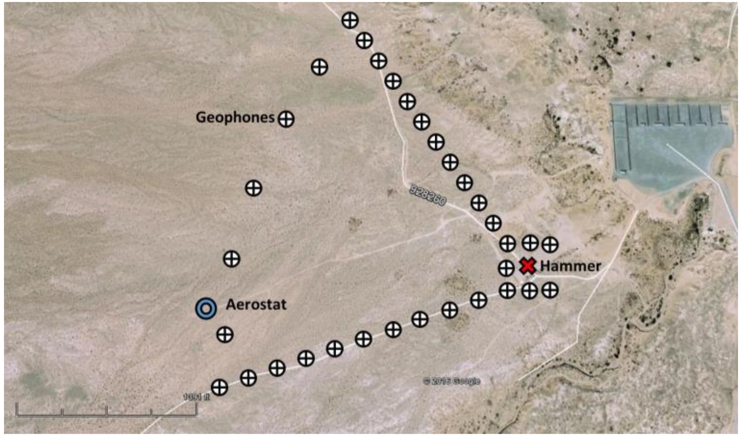
- Objective – develop technology required to discern seismicity-induced atmospheric signals using the Earth atmosphere as a Venus analog
- Advantage – we can fly multiple flights to refine our technology
- Limitation – lithosphere-atmosphere coupling on Earth is much weaker than Venus

Earth as a Venus analog – Campaign plan



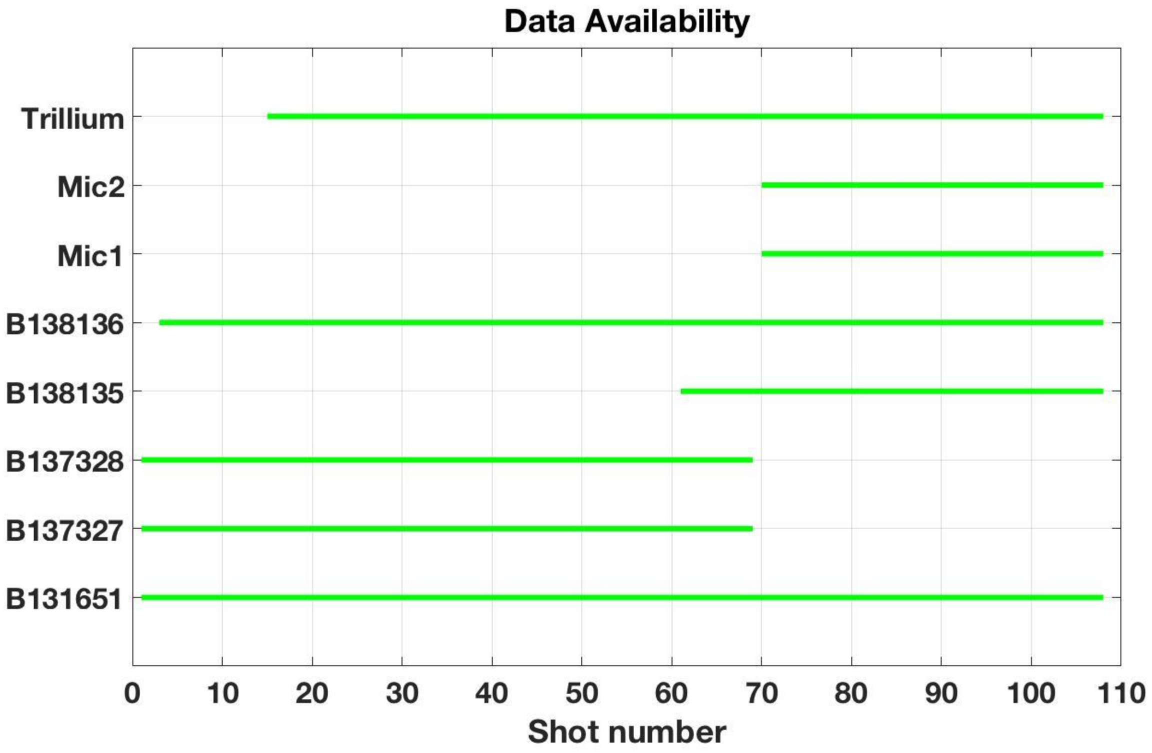
Pahrump test



- Objective – use a small but repeatable seismic source to produce artificial earthquakes, demonstrate detectability using aerial platforms at low altitude
- Sensor network included sensitive barometers, broadband seismometers, IMUs, and geophones
- 108 shots from the hammer over a period of 4 hours

Barometer data – Availability



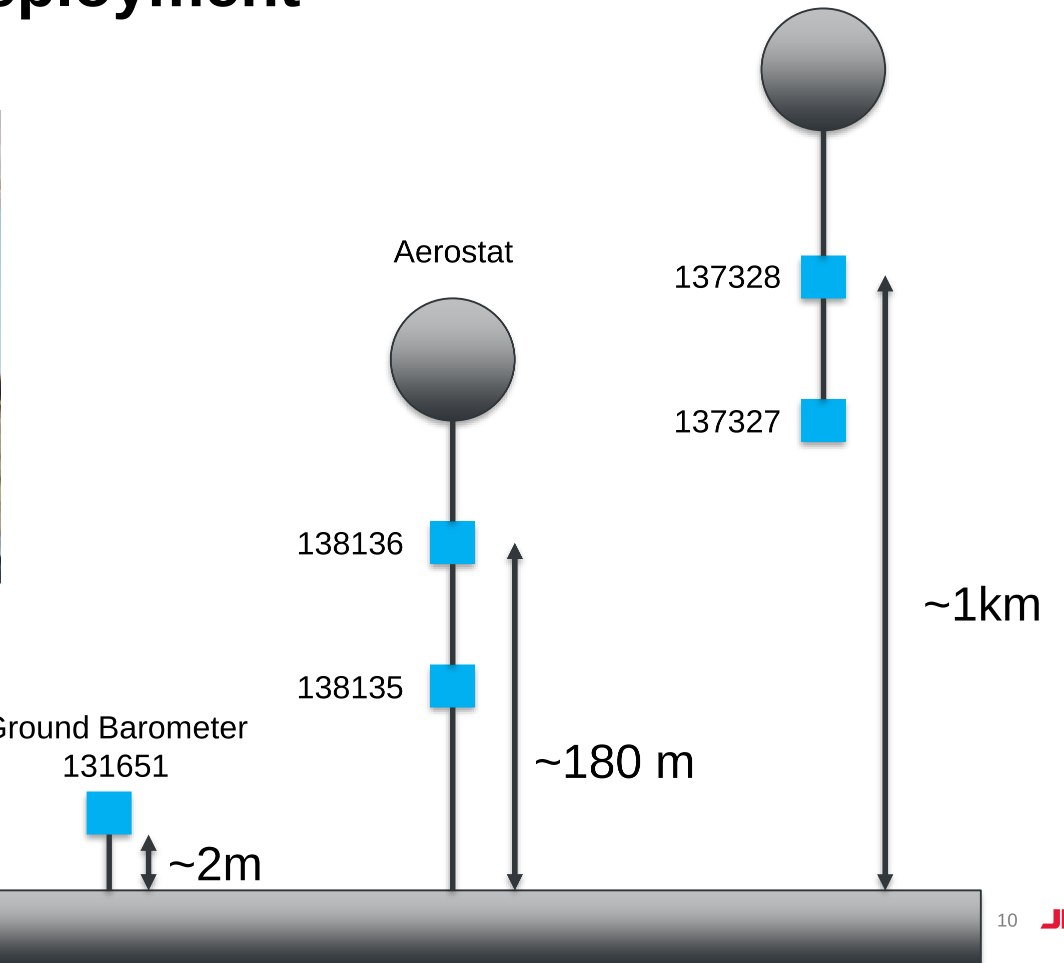
Barometer – Sensor deployment

Barometer, GPS receiver, IMU, Raspberry Pi

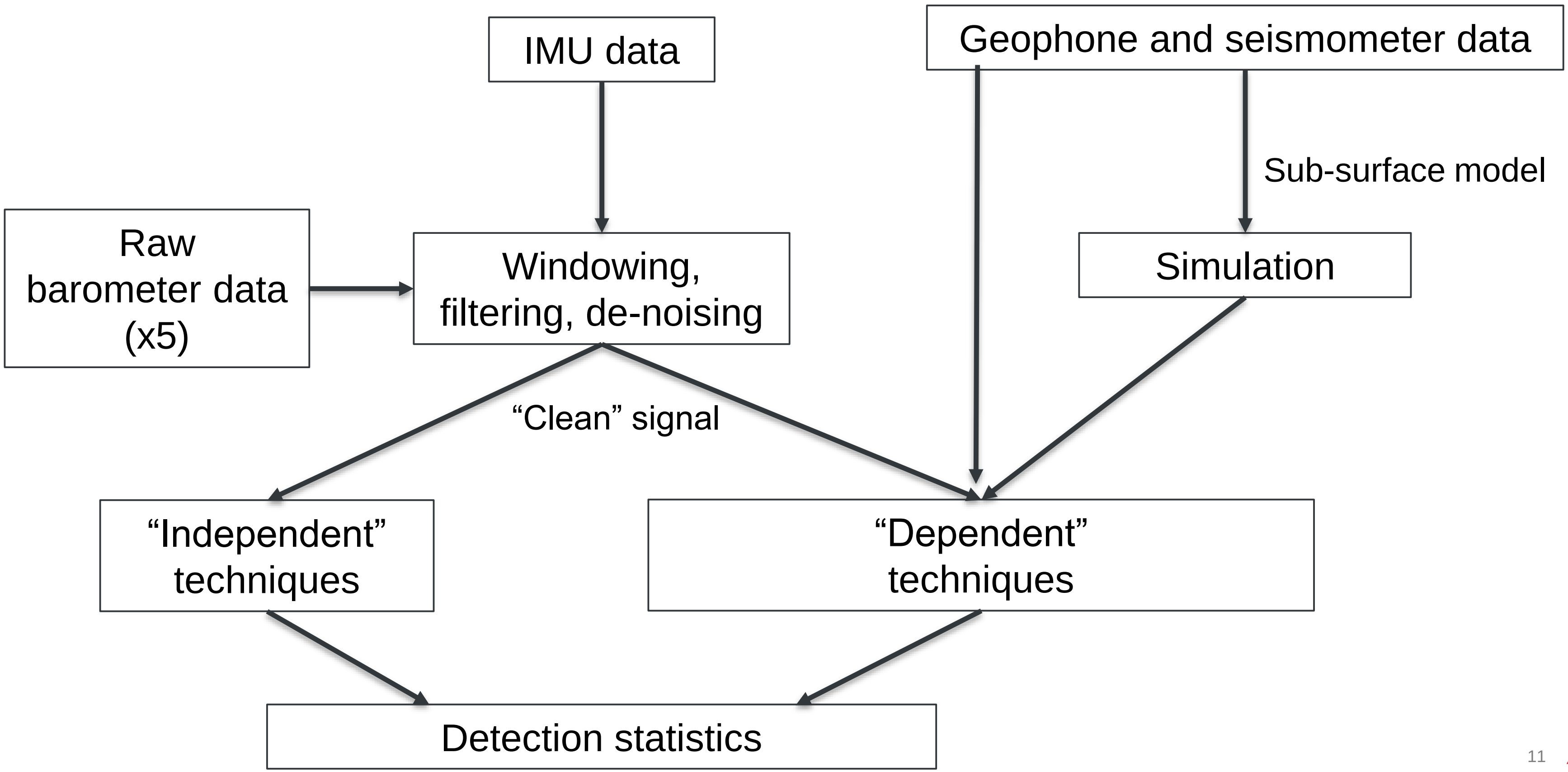
Wind noise reduction port

Seismic Hammer

Ground



Data processing methodology for Pahrump campaign

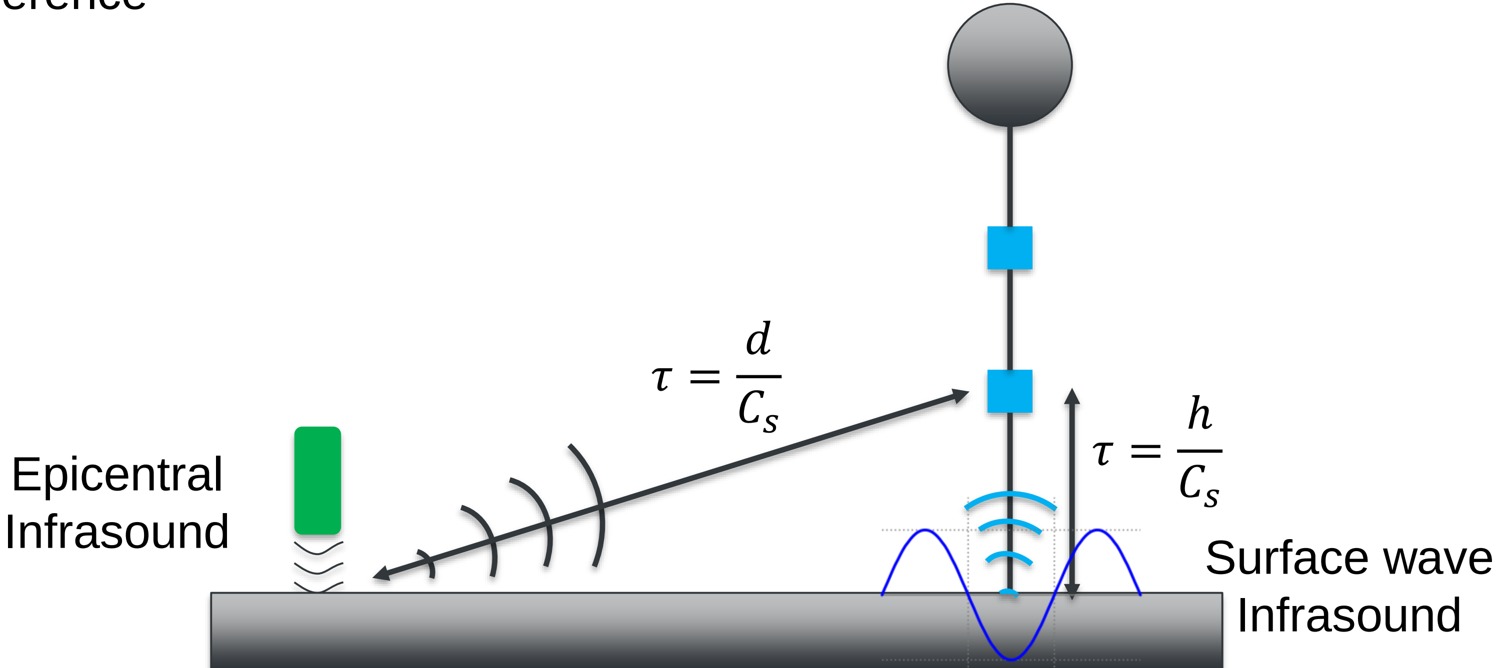


Barometer data – Analysis procedure

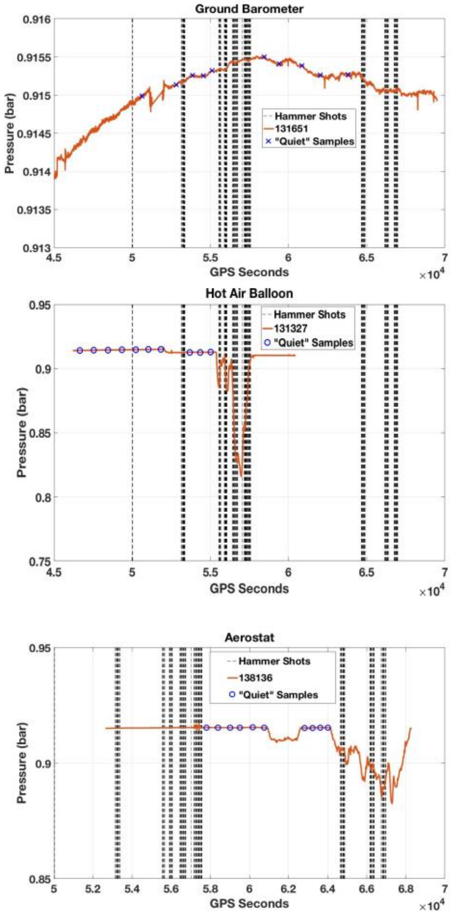
- Select quiet/non-operational periods and determine barometer noise background
- Window the barometer data near shot times. For ground barometer and aerostat, 20s windows with 25% before the shot. For hot air balloon, 30s windows
- Filter the windowed pressure with a 4 Hz high-pass (or 4-10 Hz bandpass) Butterworth filter for wind noise removal. Look through all available shots, remove unsuitable samples
- Interpolate data using cubic splines to a regular time vector with dt=10ms
- Perform further analysis

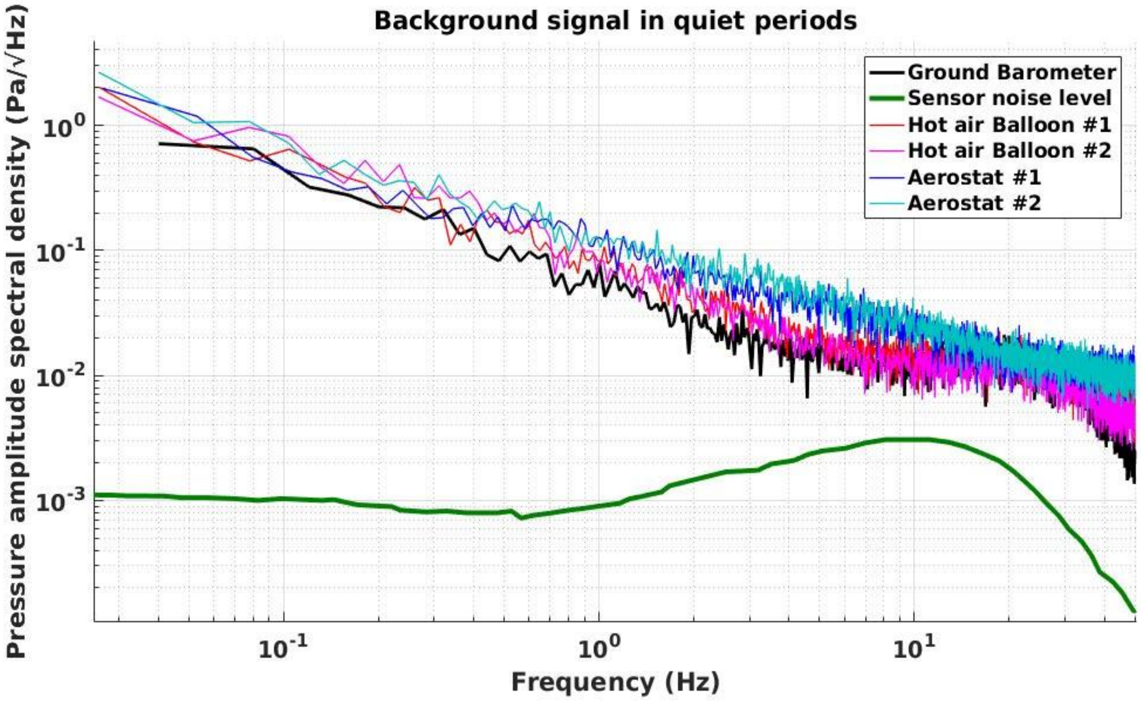
Barometer data – signal stacking

- We have multiple traces from a repeatable event – stacking will remove random, uncorrelated noise
- Signals may be aligned and averaged using the expected arrival time as a reference



Barometer data – Quiet background





Noise is lower on the floating balloon than the moored balloon

Barometer data – signal stacking

- Ground barometer is stationary – shot-relative signal arrival time is the same for all shots

- For aerostat and hot air balloon, calculate distance and arrival time from hammer based on GPS and barometer data:

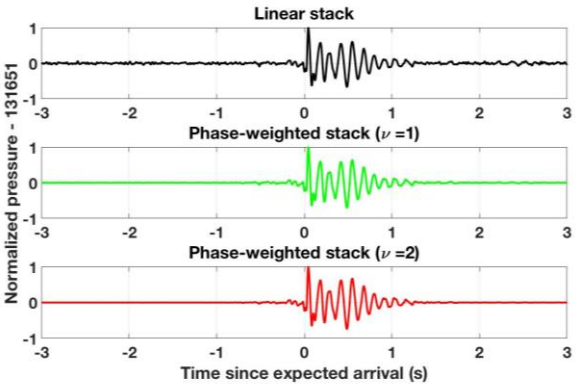
$$\mathrm{D}_x = r\sqrt{(\phi_1 - \phi_2)^2 + \cos(\phi_1)\cos(\phi_2)\,(\lambda_1 - \lambda_2)^2}$$

$$d = \sqrt{D_x^2 + h^2}$$

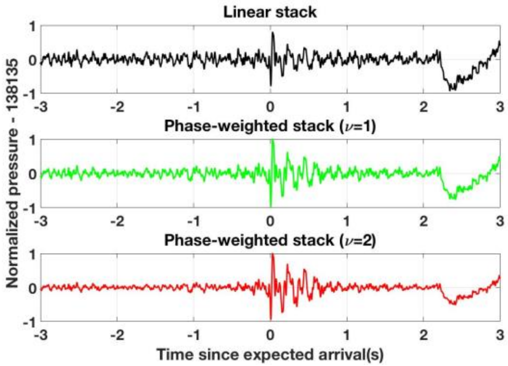
$$\tau = \frac{d}{C_s}$$

- Re-align all pressure traces such that the expected arrival time is at t=0, average all signals using linear or phase-weighted stacking

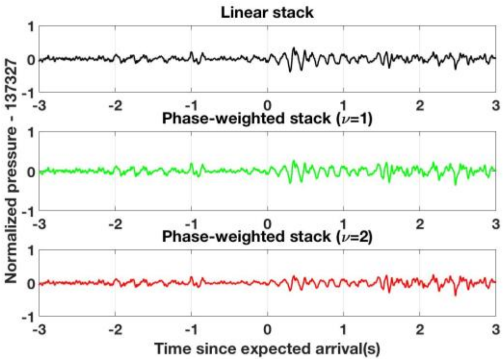
Barometer data – signal stacking results



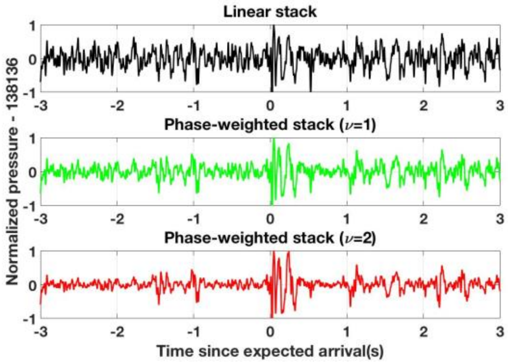
Ground barometer
108 shots



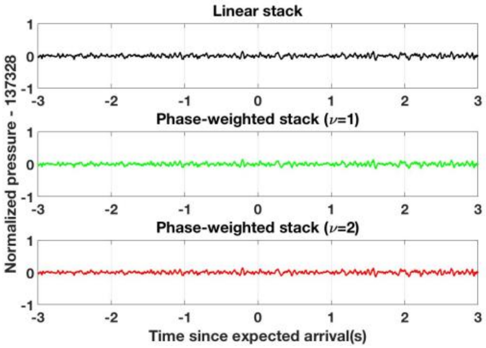
Lower aerostat barometer



Lower HAB barometer



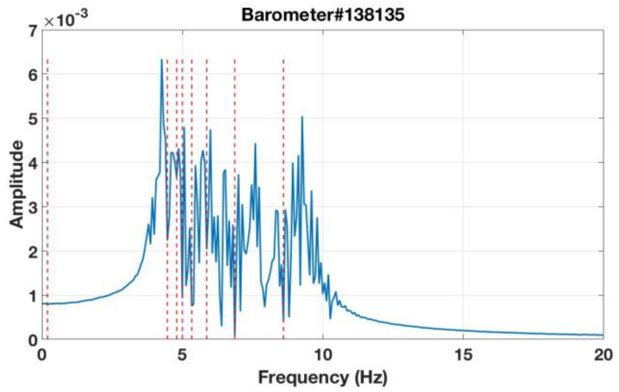
Upper aerostat barometer
30+ shots

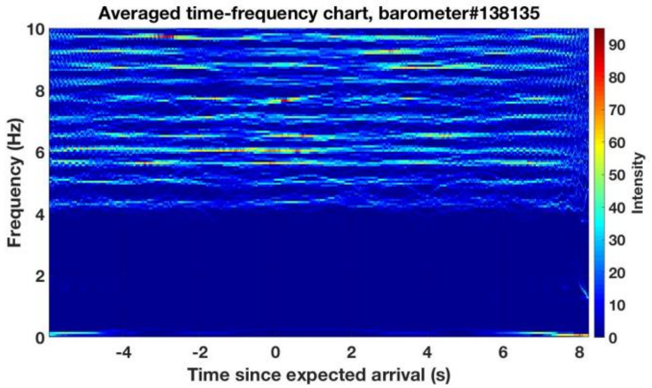


Upper HAB barometer
15+ shots

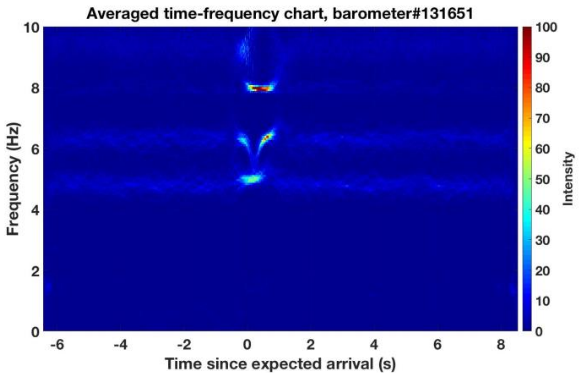
Barometer data – Time-frequency analysis

- Signal bandpassed between 4-10 Hz, analyzed in time-frequency domain using Empirical Wavelet Transform (EWT) (Gilles 2013)
- Frequency spectrum split into N contiguous segments, wavelets constructed for each segment and composite time-frequency spectrogram is generated for each shot
- EWT produces sparse spectrograms – good for pattern identification
- Mathematical details in Gilles (2013), code available online as a toolbox on Matlab FileExchange

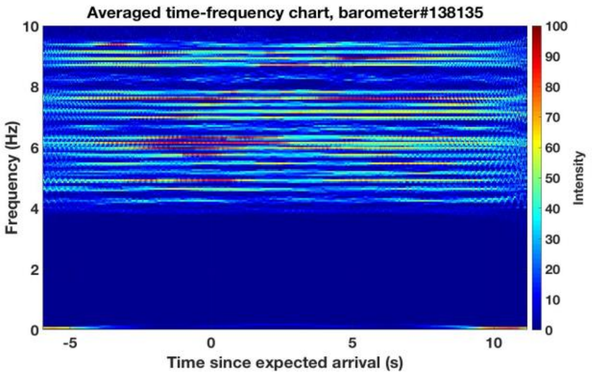




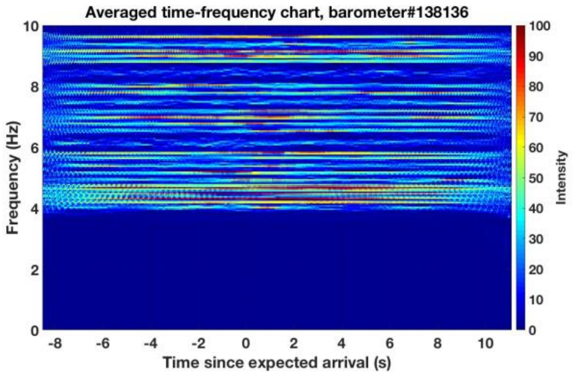
Barometer data – Preliminary EWT results



Ground barometer
(108 shots)



Aerostat (lower)
(30 shots)



Aerostat (upper)
(30 shots)

- All traces show heightened mode activity at the expected arrival time of the wave – pronounced activity in the ground barometer and the aerostat
- Hot air balloon data still being analyzed

Barometer data – Other detection ideas

- Template correlation between expected and detected waveforms – need ground truth measurements
- Correlation between surface motion and barometer spectrograms – need ground truth measurements
- De-noising of signal using IMU-derived wind speed data

Conclusions/Future Work

- Infrasound signals from epicentral motion are being detected in most of the barometers
- Current processing techniques rely on ground awareness – barometer data results can be greatly enhanced by simulation and seismometer data
- Dry Alluvium Geology (DAG) experiment in Nevada will be the next test – payload and software will be re-designed
- We aim to fly stratospheric flights in Oklahoma to detect naturally occurring earthquakes in the future
- Detection methods will steadily be made independent of ground truth (there is none at Venus)
- Infrasound is a great candidate for remote seismic measurements, especially on planets with dense atmospheres such as Venus

Acknowledgments

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Thank you

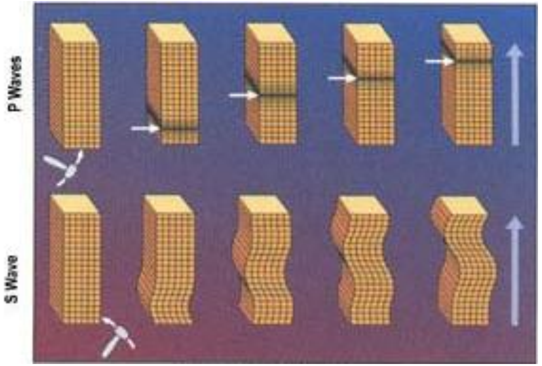
Questions?

Spares

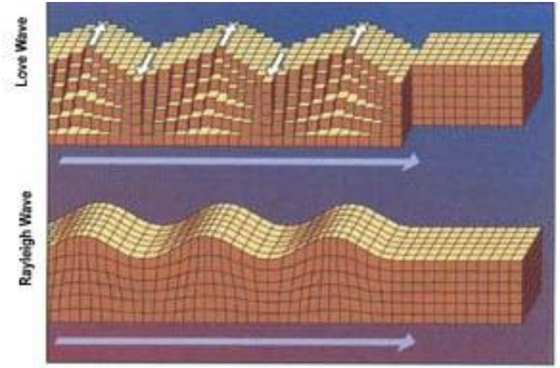
Introduction – Seismology primer

- Earthquakes produce a variety of seismic waves:
  - P and S Waves – Body waves, frequency ~1 Hz
  - Rayleigh and Love Waves – surface waves, frequency ~0.05 Hz

- Rayleigh waves travel large distances from the epicenter and produce large ground motion



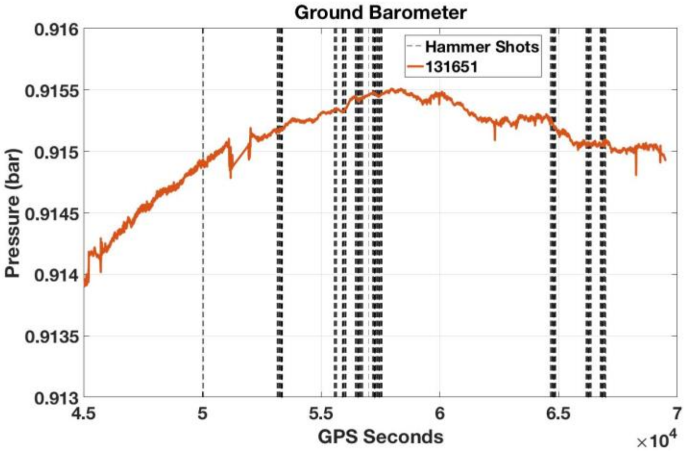
Body waves

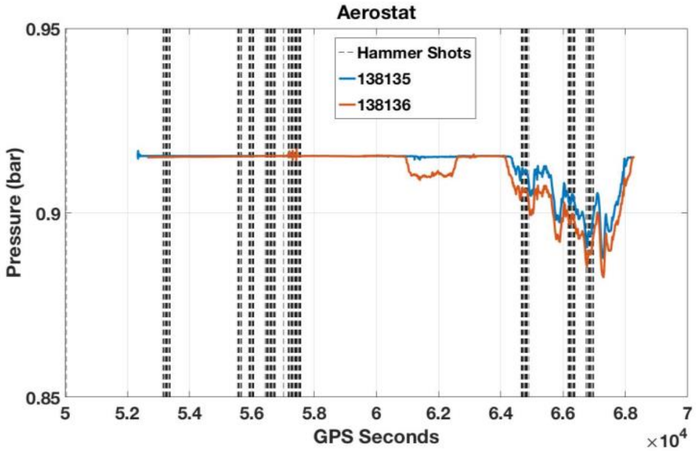


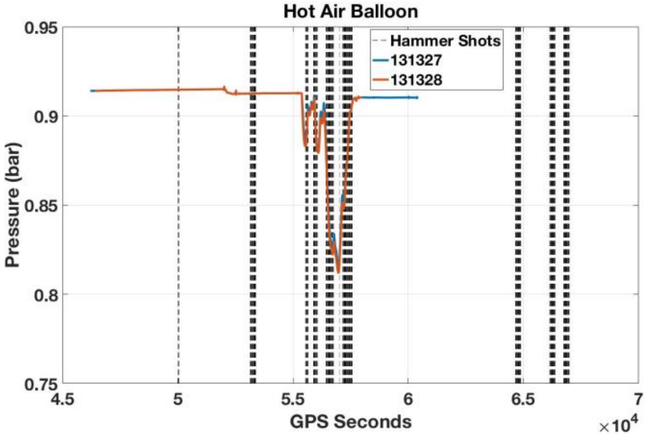
Surface waves

Wikimedia Commons (2017)

Barometer data – Full pressure trace







Barometer data – Phase-weighted stacking

- Construct an "analytical" signal from each filtered and aligned pressure trace:

$$S_j(t) = s_j(t) + j\,H\left(s_j(t)\right) = A_j(t)\exp\left(j\phi_j(t)\right)$$

- $\phi_j(t)$ is the instantaneous phase of the pressure trace. We want to emphasize parts where instantaneous phase is correlated against those where it's not.

- Build a correlation measure: $0 \le c(t) = \frac{1}{N}\left|\sum_i \exp\left(j\phi(t)\right)\right| \le 1$

- Smooth the correlation measure with windowing: $\tilde{c}(t) = \frac{1}{2T+1}\sum_{u=t-T/2}^{u=t+T/2} c(u)$

- Stack after weighting with the correlation measure: $X(t) = \frac{1}{N}\sum_{i=1}^{N} s_i(t)\tilde{c}(t)^{\nu}$

- Parameter v decides how aggressive we want to be with finding correlations

- This stacking method is nonlinear (as opposed to straight averaging)

Barometer data – signal stacking summary

- Ground barometer and aerostat barometers show strong epicentral infrasound after stacking
- Hot air balloons show weaker signal because of timing inconsistencies and burner noise
- Surface wave-related infrasound not detected yet – surface wave velocities are not well constrained as yet
- Stacking produces one instance from multiples – enhances SNR, but not good for detection statistics

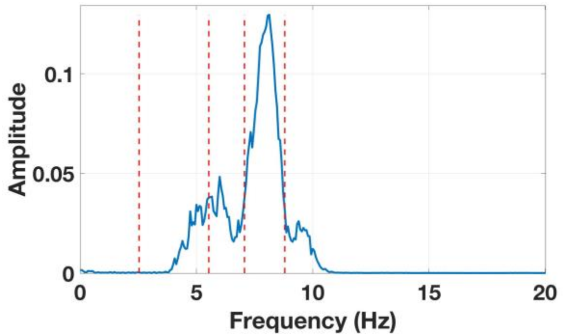
Barometer data – Empirical Wavelet Transform (EWT)

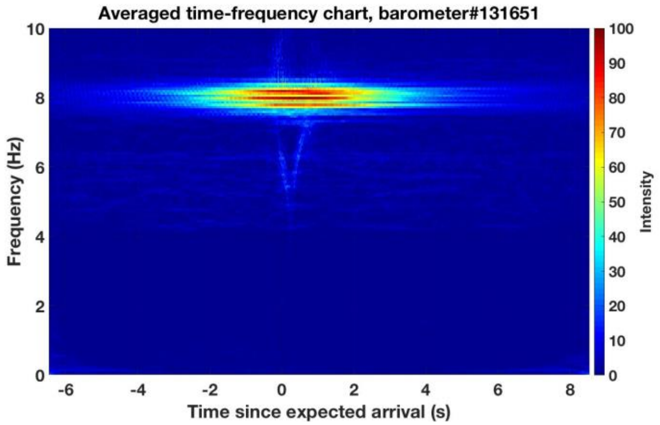
- Seismic infrasound waves appear as transients in the pressure traces – do not appear clearly in the Fourier domain
- Time-frequency analysis is needed to identify non-stationary components – wavelet transform is the best way to do this
- Limitation: Mother-wavelet function must be pre-selected
- New method called Empirical Wavelet Transform (EWT) adapts the wavelets to the frequency content of the data without assumptions about type of data. See Jerome Gilles (2013)
- Has been recently used in seismic waveform analysis (Liu et al. 2016)

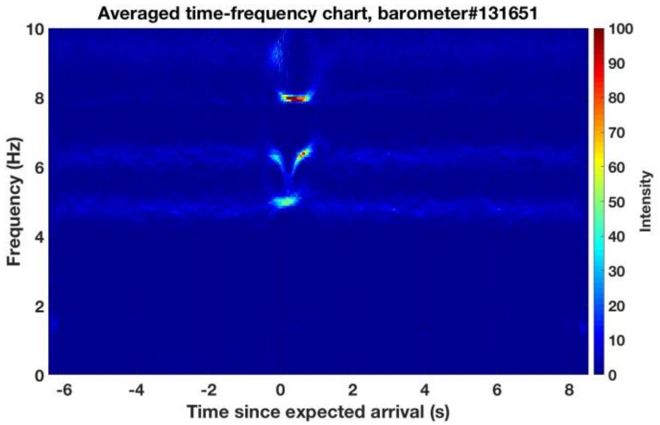
Barometer data – EWT – Smarter segmentation

- Identify shot traces with the clearest signal
- Compute average Fourier spectrum
- Increase N till majority of the peaks are segmented
- Form EWT filter bank around these N segments
- Perform time-frequency analysis based on this segmentation for the rest of the shots

Barometer data – Smarter segmentation

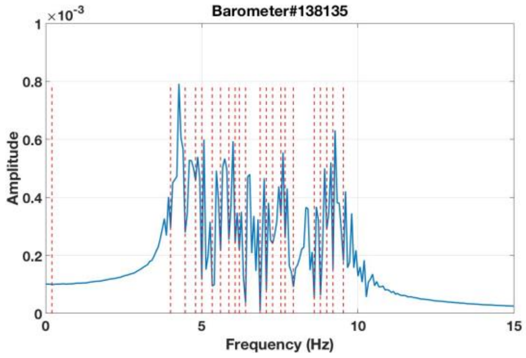


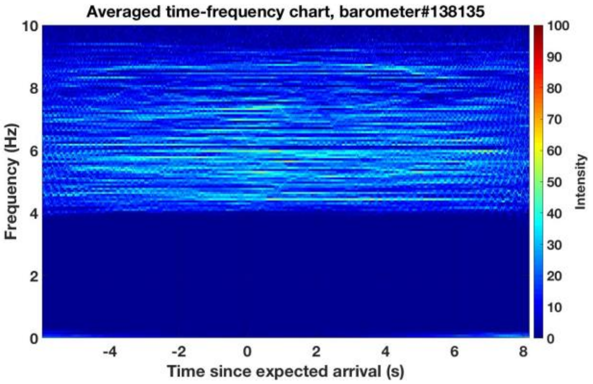




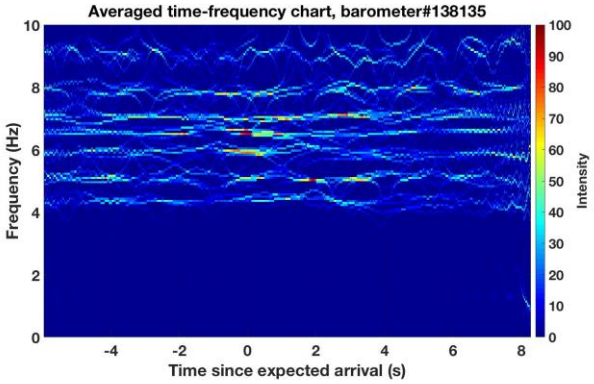
Ground barometer (N=5)

Barometer data – Smarter segmentation

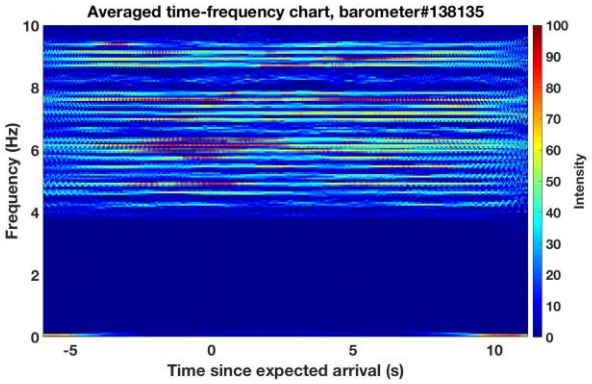




30 shots, old



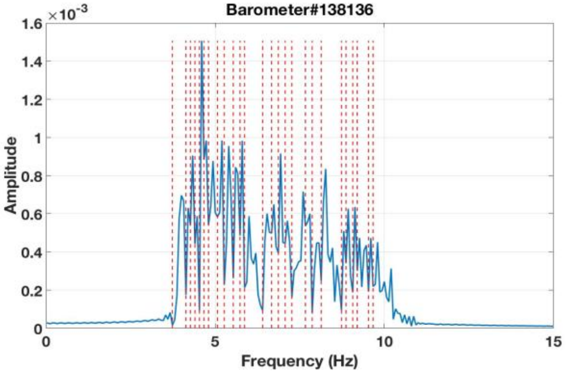
8 best shots, new

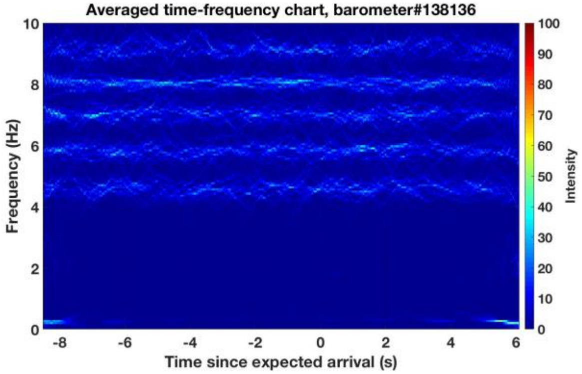


30 shots, new

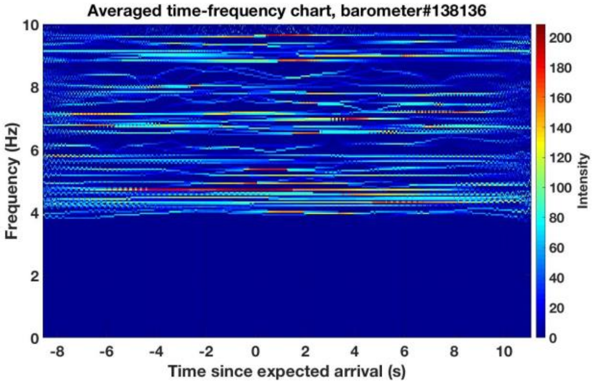
Aerostat – lower (N=23)

Barometer data – Smarter segmentation

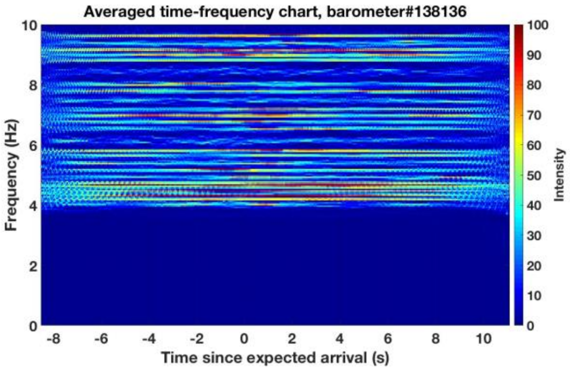




30 shots, old



3 best shots, new



30 shots, new

Aerostat – upper (N=27)

Barometer data – EWT – Summary and path forward

- After smart segmentation, stacked spectrograms for the ground barometer and both aerostat balloons show modal activity at the expected arrival time of epicentral infrasound
- Segmentation affects the spectrogram – need a mathematically consistent way to choose the number of segments
- Need to pick out relevant bands from stacked spectrogram and analyze each signal individually
- Hot air balloon timing issues to be resolved before implementing this solution
- Lesson learned – a clean signal is worth its weight in gold